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Soil Nail Wall Design using Simplified Charts

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Abstract. Soil nailing is one of the most commonly used in-situ earth retaining technique being used worldwide. Due to its widespread applications, over the years, numerous methods of analysis and design of soil nail walls has evolved. The design of any soil nail wall is a function of multiple factors including geometric configuration of wall, loading conditions, in-situ soil conditions, and numerous inherent failure modes. In practice, usually analytical methods based on allowable stress design approach are used for the design of soil nail walls. In this study, following the most commonly used allowable stress design method for soil nail walls, design charts are proposed for assisting in the design process. Charts are prepared for a variety of geometric conditions of wall, such as face batter & height of wall, and in-situ soil conditions. These charts can also be used for preliminary design and evaluation of the internal stability failure modes, namely, pullout failure and tensile failure. The application of the proposed design charts is demonstrated with the help of an illustrative design example of a typical soil nail wall. It is anticipated that the proposed chart would assist practicing engineers.

Keywords: Soil Nailing, Allowable Stress Design, Design Charts

1 Introduction

Soil nailing is one of the most widely used in-situ earth retaining technique. Typical geotechnical engineering applications of soil nailing technique include stabilization of road/rail side slopes, landslides, bridge abutments, and vertical cuts for basement excavations and approach roads for subways [1-6].

Over the years, with the extensive use of soil nailing technique, various design methodologies evolved and are being used extensively in practice. In literature, a number of the prominent design methodologies [7-14] for the analysis and design of soil nail walls are readily available. However, for soil nail wall design in practice, very limited information in the form of charts and tables is readily available. In this study, using allowable stress design approach [12], simplified design charts are proposed that can facilitate easy design of soil nail walls and also assist in internal stability analysis. The proposed design charts are prepared by considering a variety of geometric and in-situ soil conditions.

2 Failure Modes of Soil Nail Walls

Various failure modes [12] for a typical soil nail wall can be broadly classified into three distinct groups as: external failure modes, internal failure modes and facing failure modes. The two prominent external failure modes of soil nail walls are global stability and sliding stability. Global stability refers to the overall stability of the reinforced soil nail wall mass. On the other hand, sliding stability indicates the sliding resistance along the base of the soil nail wall in response to the additional lateral earth pressure mobilized due to the excavation. Further, the two most prominent internal failure modes of soil nail walls are nail-soil interface pullout failure (simply, pullout failure) and tensile failure of nail tendon (i.e. reinforcing element). Pullout failure occurs due to insufficient intrinsic bond strength and / or insufficient nail length in the passive zone. Tensile failure of a soil nail takes place when the maximum tensile axial force in the soil nail is greater than the nail tensile capacity. Facing failure modes are not considered in present study being often attributed to the poor construction practices more than the in-situ soil, boundary and loading conditions. A detailed discussion on various failure modes is readily available in literature [12, 15]. Table 1 shows minimum recommended factors of safety for various external and internal failure modes.

Table 1. Minimum recommended factors of safety for soil nailing [12].

Mode type	Failure type	Symbol	Factors of safety
External	Global stability	FS_G	1.35-1.50
	Sliding stability	FS_{SL}	1.30-1.50
Internal	Nail pullout failure	FS_P	2.00
	Nail tensile failure	FS_T	1.80

In the present study, design charts are proposed to address the following four prominent failure modes: (a) global stability, (b) sliding stability, (c) pullout failure and (d) nail tensile failure. Allowable stress design (ASD) methodology is adopted for obtaining expressions of factor of safety for each of the above failure modes of soil nail walls. As shown in Fig. 1, a simplified single wedge failure mechanism is assumed to be inclined at an angle $\psi = 45 + (\phi/2)$ with respect to horizontal, where ϕ is the angle of internal friction of the in-situ soil [12, 16].

2.1 Global stability

Referring to the Fig. 1, the general expression of factor of safety for global stability FS_G is given by Eq. (1).

$$FS_G = \frac{\sum R}{\sum D} = \frac{cL_F + T_{eq}\cos(\psi - i) + \left[(W + Q_T)\cos\psi + T_{eq}\sin(\psi - i)\right]\tan\phi}{(W + Q_T)\sin\psi} \tag{1}$$

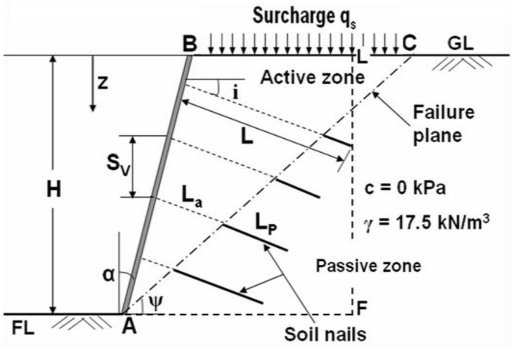


Fig. 1. Schematic reference diagram for design charts.

where: ΣR and ΣD = summation of resisting and driving forces along the potential failure plane *AC* having length L_F, respectively; c = in-situ cohesion (*kPa*); i (*degrees*) = nail inclination with respect to horizontal; W (*kN/m*) = weight of failure wedge *ABC*; Q_T (*kN/m*) = total surcharge load; and $T_{eq}\left(kN/m\right) = \frac{1}{S_h}\sum_{j=1}^{n}\left(T_{all}\right)_j$ = equivalent nail force, where: T_{all} is the *minimum* of pullout capacity R_P and tensile capacity R_T given by Eqs. (2) and (3) respectively of the nail j embedded at depth z out of the total n nails embedded at different depths in a section.

$$\left(R_P\right)_z\left(kN\right) = \left(\pi D L_P\, q_u\right)/1000 \tag{2}$$

$$\left(R_T\right)_z\left(kN\right) = \left(0.25\pi d^2 f_y\right)/1000 \tag{3}$$

where: q_u = ultimate bond strength [*kPa*]; f_y = yield strength of steel [*MPa*]; D (*m*) = drill-hole diameter D_{DH} (in case of grouted nails) or tendon diameter d (in case of driven nails); and for nail length L (*m*), effective bond length L_P (*m*) is given by Eq. (4).

$$(L_P)_z = L - \left[\frac{(H-z)\cos\psi}{\sin(\psi + i)}\right] \tag{4}$$

2.2 Sliding stability

Referring to the Fig. 1, expression of factor of safety for sliding stability FS_{SL} is given by Eq. (5).

$$FS_{SL} = \frac{\sum R}{\sum D} = \frac{c_b\left(AF\right) + \left(W' + Q_T'\right)\tan\phi_b}{P} \tag{5}$$

where: ΣR and ΣD = summation of resisting and driving forces along the potential failure plane *AF*, respectively; for the rigid sliding block *ABLF*: c_b and ϕ_b = cohesion and friction angle along the base (*AF*), respectively; *W'* (*kN/m*) = its weight; Q'_T (*kN/m*) = q_s x *BL* = total surcharge load acting on it; and *P* (*kN/m*) = total lateral active thrust acting behind it.

$$P = \frac{\gamma H^2}{2} K_a \left[1 + \frac{2q_S}{\gamma H} \right] \tag{6}$$

where: K_a = coefficient of Rankine's lateral active earth pressure; q_s (*kPa*) = distributed surcharge loading, *H* (*m*) = vertical height of the soil nail wall; and γ (kN/m^3) = insitu soil unit weight.

2.3 Pullout failure mode

The expression for factor of safety against pullout failure FS_P is given by Eq. (7).

$$(FS_P)_z = \frac{(R_P)_Z}{(T)_Z} \tag{7}$$

where: $(R_P)_z$ is as determined by Eq. (2); and the maximum axial force *T* at depth z can be obtained as:

$$(T)_z\,(kN) = K_a (q_s + \gamma z) S_h S_v \tag{8}$$

2.4 Nail Tensile failure mode

The expression for factor of safety against nail (tendon) tensile failure FS_T is given by Eq. (9).

$$(FS_T)_z = \frac{(R_T)_Z}{(T)_Z} \tag{9}$$

where: $(R_T)_z$ and $(T)_z$ are as determined by Eq. (3) and Eq. (8), respectively.

3 General Design Procedure

In general, the design procedure for a soil-nail wall includes the following steps:

1. For the specified structure geometry (depth and cut slope inclination), ground profile, and boundary (surcharge) loadings, working nail forces are estimated and location of the potential failure surface are determined.
2. Selection of the reinforcement type (type, cross-sectional area, length, inclination, and spacing) is done and verification of local stability at each reinforcement level is assured. Further, global stability of the nailed-soil structure is also done.

3. Estimation of the system of forces acting on the facing (i.e., lateral earth pre sure and nail forces at the connection) and hence, design of the facing for specified architectural and durability criteria is to be carried out.
4. For permanent structures, corrosion protection relevant to site conditions is selected. Also, the suitable drainage system for groundwater piezometric levels is adopted.
5. A few of the usual guidelines for preliminary design of soil nail wall are presented in Table 2.

Table 2. Recommended guidelines for soil nail wall preliminary design [12].

Item	Recommended guideline
Nail installation process	Drilled and Grouted / Driven
Nail spacing	Grouted nails: 1.25 *m* to 2 *m*; Driven nails: 0.5 *m* to 1.20 *m*. Influence area: (Horizontal, S_h x vertical, S_v) $\leq 4m^2$
Nail diameter	Grouted nails: 100 – 200 *mm* drillhole diameter for grouted nails with minimum 20 *mm* reinforcement bar. Driven nails: 20 *mm* to 36 *mm* reinforcement bar
Nail length	Usually 0.6 to 0.8 times the vertical wall height, *H*
Nail inclination (wrt horizontal)	10 to 20 *degree*s (usually 15 *degrees*)
Nail pattern at wall face	Square or staggered
Yield strength of nail tendon	$\geq$ 415 *MPa*
Unconfined compressive strength of grout / shotcrete	$\geq$ 20 *MPa*
Minimum cover to reinforcement for corrosion protection	25 *mm* (minimum)
Temporary facing thickness	75 *mm* – 100 *mm* (shotcreted welded wire mesh)
Permanent facing thickness	150 *mm* – 200 *mm* (cast in situ RCC or precast concrete facing)
Wall face batter (wrt vertical)	0 to 10 *degrees*

4 Design Charts for Soil Nail Walls

A series of charts have been prepared as a design aid to provide most frequently required parameters in the design of soil nail walls. It is worth stating that these charts are only applicable for the conditions they are developed for. Details of the range of variables considered for the development of the design charts are as shown in Table 3. Design charts are developed with reference to Fig. 1 and are based on the following assumptions.

a. Single wedge failure mechanism (see Fig. 1) with failure plane inclined at an angle $\psi = 45 + (\phi/2)$ (in degrees) w.r.t. the horizontal is considered.

b. In-situ soil is considered to be dry, cohesionless and homogenous. It is reported in the literature [15, 17] that unit of soil has negligible influence on the significant failure modes of soil nail walls. Therefore, all charts have been prepared for the fixed value of the unit weight of in-situ soil $\gamma = 17.5 kN/m^3$.

c. A nominal inclination of about 10-15^o is usually provided to the grouted soil nails to facilitate grout flow through gravity. Inclination of nails mobilizes the bending and shearing resistance of the nails; however, this has negligible influence on the overall stability [12]. Therefore, charts are prepared assuming a fixed nail inclination $i = 15^o$ with respect to the horizontal.

d. Soil nail wall is subjected only to the dead load due its self-weight and backslope is considered to be horizontal i.e. $\beta = 0$.

Table 3. Details of various design charts and their application.

Design chart shown in		Variable(s)	Unit	Variable range (or values)	Output parameter
Fig. 2	(a)	Vertical height of the wall, H	*m*	0 – 20	Max. axial force per unit nail influence area t_{max}.
	(b)	Angle of internal friction, ϕ	*degrees*	20, 24, 28, 32, 36	
Fig. 3(a-b)	(a)	Face batter, α	*degrees*	0, 10	Nail length in the active zone L_a embedded at depth *z*.
	(b)	Angle of internal friction, ϕ	*degrees*	20, 24, 28, 32, 36	
Fig. 4(a-e)	(a)	Normalised bond strength, μ	--	0.10,0.15, 0.25, 0.35, 0.45	Minimum pullout length $L_{P, min}$ (i.e. length of nail in the passive zone) required at any embedment depth *z*.
	(b)	Angle of internal friction, ϕ	*degrees*	20, 24, 28, 32, 36	
Fig. 5(a-f)	(a)	L / H ratio	--	0.6, 0.7, 0.8	Available pullout length $L_{P, avail}$ at any embedment depth *z*.
	(b)	Face batter, α	*degrees*	0, 10	
	(c)	Angle of internal friction, ϕ	*degrees*	20, 24, 28, 32, 36	
Fig. 6	(a)	Characteristic strength of steel, f_y	*MPa*	250, 415, 500	Nail tensile capacity R_T.
	(b)	Nail or reinforcement bar diameter, *d*	*mm*	6-36	

Note:

Normalized bond strength, $\mu = \frac{q_u D}{FS_P \gamma S_h S_v}$; Maximum axial force per unit nail influence area, $t_{\max} = \left(\frac{1-\sin\phi}{1+\sin\phi}\right)\gamma H$; Maximum design axial force, $T_{\max} = t_{\max} S_h S_v$; Equivalent height for surcharge, $h_{eq} = {q_s}/{\gamma}$.

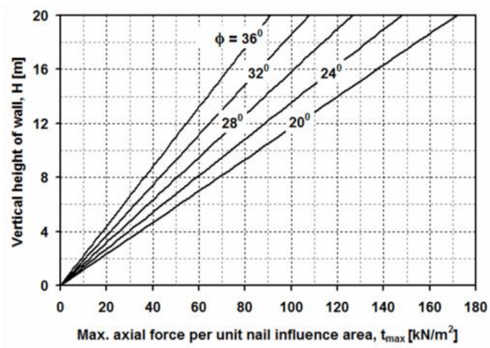
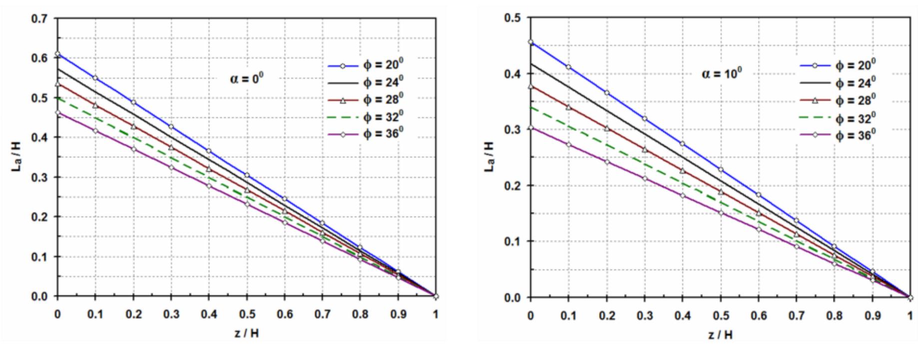


Fig. 2. Determination of maximum axial tensile force per unit nail influence area (t_{max}) with vertical height of the soil nail wall (H).



(a) for $\alpha = 0^0$ (b) for $\alpha = 10^0$

Fig. 3. Determination of nail length in active zone (L_a) with depth of embedment of nail (z).

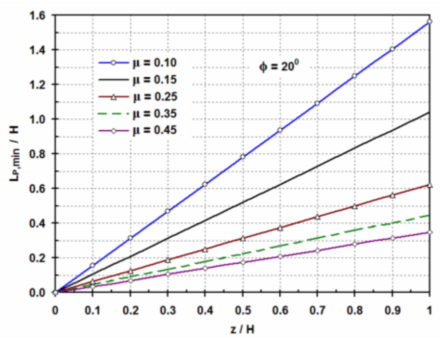
5 Applications of the Proposed Design Charts

The proposed design charts can be suitably used for the following purposes:

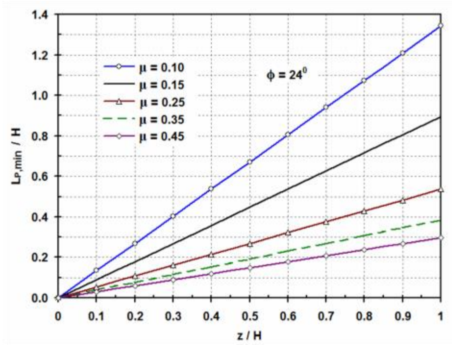
a. Preliminary design to obtain preliminary nail length L and maximum design tensile force T_{max} using charts shown in Fig. 2, Fig. 3(a-b), and Fig. 4 (a-e), accordingly. Minimum length of soil nail L is adopted as the maximum of L_1 and L_2: $L_1 = L_a + L_{P,\min}$ and L_2 = 0.6H. It is to be noted that $L_{P,min}$ shall be determined with respect to the topmost nail.

b. To obtain available pullout length L_P, avail using charts shown in Fig. 4(a-e) and Fig. 5(a-f), which is required for: (i) determination of equivalent nail force T_{eq} for obtaining global stability, and (ii) check for pullout failure mode at each nail level.

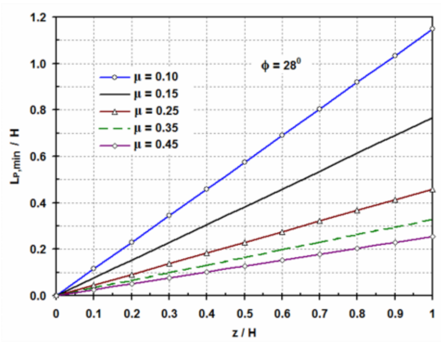
c. To obtain nail tensile capacity R_T required for checking nail tensile failure mode using charts shown in Fig. 2 and Fig. 6.



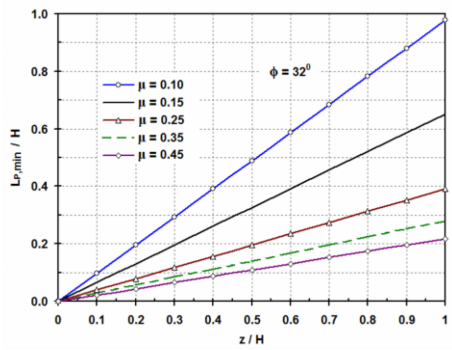
(a) for $\phi = 20^0$



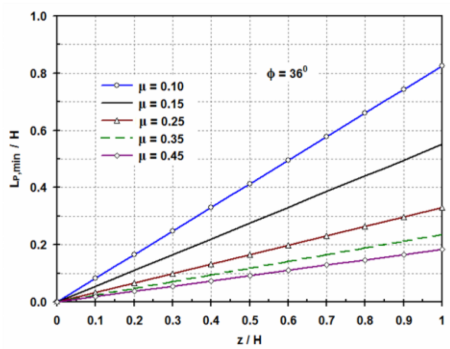
(b) for $\phi = 24^0$



(c) for $\phi = 28^0$

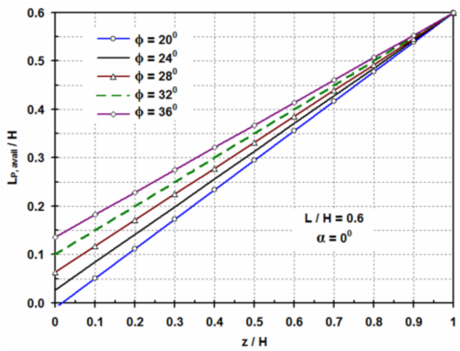


(d) for $\phi = 32^0$

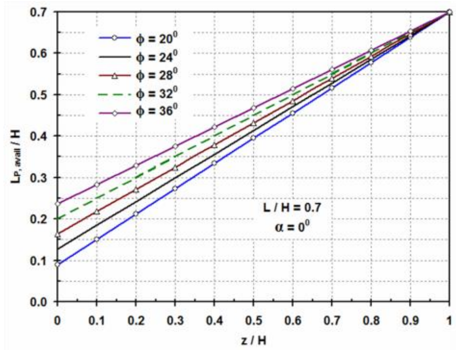


(e) for $\phi = 36^0$

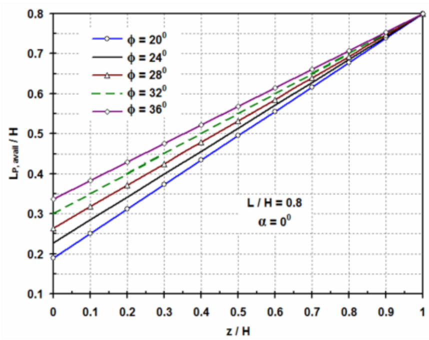
Fig. 4. Determination of minimum pullout length ($L_{P,min}$) i.e. length of nail in passive zone with depth of embedment of nail (z).



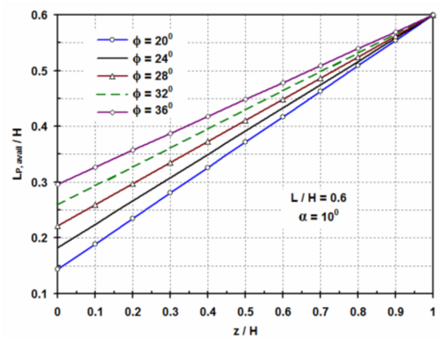
(a) for $L/H = 0.6$ and $\alpha = 0^0$



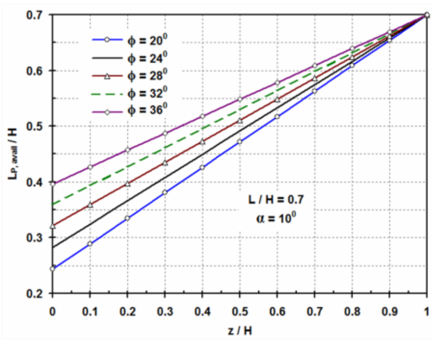
(b) for $L/H = 0.7$ and $\alpha = 0^0$



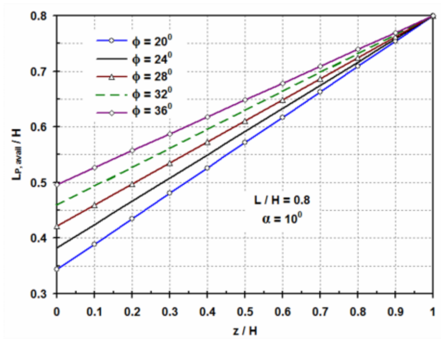
(c) for $L/H = 0.8$ and $\alpha = 0^0$



(d) for $L/H = 0.6$ and $\alpha = 10^0$



(e) for $L/H = 0.7$ and $\alpha = 10^0$



(f) for $L/H = 0.8$ and $\alpha = 10^0$

Fig. 5. Determination of available pullout length ($L_{P,avail}$) i.e. length of nail in passive zone with depth of embedment of nail (z)

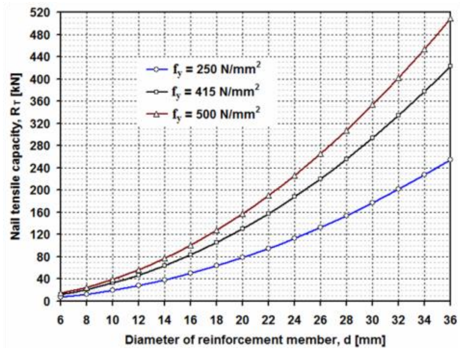


Fig. 6. Determination of nail tensile capacity (R_T) with diameter of tendon in soil nail (d).

6 Illustration of Typical Soil Nail Wall Design using Charts

Using the charts as developed in the earlier sections, a design example for a typical soil nail wall is presented. For the known soil nail wall parameters, including both geometric and soil conditions, required nail (rebar) diameter & length are obtained. Also, internal failure modes namely pullout failure and nail tensile failure modes are evaluated at each nail level.

Known Soil Nail Wall Parameters

(a) Vertical height of wall: H = 8 m

(b) Face batter: α = 0.0 *degrees*; Backslope angle: β = 0.0 *degrees*

(c) Soil nail spacing: $S_h = S_v$ = 1.5 m (Note: vertical spacing of first nail S_{v1} = 0.75 m)

(d) Soil nail inclination: i = 15 *degrees*

(e) Drill hole diameter: D_{DH} = 130 mm

(f) Soil nail material: Grade Fe415; f_y = 415 MPa

(g) Representative soil properties from soil investigation report:

Soil type: dense to very dense silty sands; Cohesion: c = 0 kPa; Friction angle: $\phi = 32^0$; Unit weight: $\gamma = 17.5 kN/m^3$; ultimate bond strength: q_u = 100 kPa.

Nail (Rebar or Tendon) Diameter d

From Fig. 2, for H = 8 m, $\phi = 32^0$, t_{max} = 43 kN/m^2

Therefore, maximum design axial force, $T_{\max} = t_{\max} S_h S_v$ = 43 x 1.5 x 1.5 = 96.75 kN.

For a minimum factor of safety of against nail tensile failure FS_T = 1.80, the required cross-sectional area A_t of the nail bar can be determined as:

$$A_t\left[mm^2\right] = \frac{T_{\max} FS_T}{f_y} = \frac{96.75 \times 1000 \times 1.80}{415} = 419.63$$

Select reinforcement bar of diameter d = 25 mm providing cross sectional area A_t = 490 mm^2 (> 419.63 mm^2).

Nail Length L

Minimum length of soil nail L is adopted as the maximum of L_1 and L_2: $L_1 = L_a + L_{P,\min}$ and $L_2 = 0.6H$.

Here: $z = S_{v1} = 0.75\ m$ (i.e. topmost nail)
For $z/H = 0.75/8 = 0.09$, $\alpha = 0.0$; using Fig. 3a, $L_a = 0.45H$
Further, for $FS_P = 2.0$, $D = D_{DH} = 0.13\ m$;

$$\mu = \frac{q_u D}{FS_P \gamma S_H S_V} = \frac{100 \times 0.13}{2 \times 17.5 \times 1.5 \times 1.5} = 0.16$$

for $\mu = 0.16$, $z/H = 0.09$; using Fig. 4d, $L_{P,min} = 0.06H$
Therefore, $L_1 = 0.45H + 0.06H = 0.51H$ and $L_2 = 0.6H$
Hence, adopt nail length: $L = 0.6H = 0.6 \times 8 = 4.20\ m$.

Evaluation of Internal Stability. To evaluate the internal stability i.e. checking for required factors of safety against nail pullout and tensile failures at each nail level, the charts given in Figs. 5 and 6 can be used to determine pullout capacity and tensile capacity of nails installed at different levels. For the current illustrative example, from the chart given in by Fig. 5a, available length in passive zone i.e. $L_{P,avail}$ is obtained at different levels. Similarly, from the chart given in by Fig. 6, nail tensile capacity can be obtained for the known nail diameter and yield strength. Table 4 summarizes the internal stability computations for the illustrative example.

Table 4. Evaluation of the internal stability of illustrative soil nail wall using charts.

Nail no.	z [m]	z/H ratio	$L_{P,avail}/H$ (from Fig. 5a)	$L_{P,avail}$ [m]	R_P [kN] (using Eq. 2)	T [kN] (using Eq. 9)	FS_P (using Eq. 8)	R_T [kN] (from Fig. 6)	FS_T (using Eq. 9)
1	0.75	0.1	0.15	1.20	49.01	9.07	5.40	200	22.05
2	2.25	0.3	0.25	2.00	81.68	27.22	3.00	200	7.34
3	3.75	0.5	0.35	2.80	114.35	45.37	2.52	200	4.41
4	5.25	0.7	0.45	3.60	147.03	63.52	2.31	200	3.15
5	6.75	0.8	0.50	4.00	163.36	81.66	2.00	200	2.45

7 Conclusions

Considering the widespread use of soil nailing technique, it is desirable that design aids in the form of charts and tables be readily available for the practicing engineers. As a contribution to this important aspect, this study proposed a set of charts for variety of geometric and in-situ soil conditions based on one of the most popular design methodology in practice. From the illustrative design example, it is evident that the simplified charts similar to those proposed in the present study can be easily used for the preliminary design of soil nail walls, and also assist in the evaluation of the prominent internal failure modes, namely pullout failure and tensile failure.

References

1. Briaud, J.L., Lim Y.: Soil nailed wall under piled bridge abutment: simulation and guidelines. Journal of Geotechnical and Geo-Environmental Engineering 123(11), 1043-1050 (1997).
2. Wong, I.H., Low, B.K., Pang, P.Y., Raju, G.V.R.: Field performance of nailed soil wall in residual soil. Journal of Performance of Constructed Facilities 11(3), 105–112 (1997).
3. Murthy, B.R.S., Babu, G.L.S., Srinivas, A.: Analysis of prototype soil nailed retaining wall. Ground Improvement 6(3), 129–136 (2002).
4. Turner, J.P., Jensen, W.G.: Landslide stabilization using soil nail and mechanically stabilized earth walls: Case study. Journal of Geotechnical and Geo-Environmental Engineering 131(2), 141–150 (2005).
5. Yang, Y.: Remediating a soil-nailed excavation in Wuhan, China. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering 160(4), 209–214 (2007).
6. Babu, G.L.S., Rao, R.S., Dasaka, S.M.: Stabilisation of vertical cut supporting a retaining wall using soil nailing: A case study. Ground Improvement 11(3), 157–162 (2007).
7. FHWA-SA-93-026: French national research project Clouterre – Recommendations Clouterre, English Translation by Federal Highway Administration (FHWA), Washington D.C. (1991).
8. HA68/94: Design methods for the reinforcement of highway slopes by reinforced soil and soil nailing techniques, Highway Agency, United Kingdom (1994).
9. BS8006: Code of practice for strengthened/reinforced soils and other fills, British Standards Institution (BSI), London (1995).
10. pr EN 14490: Execution of special geotechnical works – Soil nailing, European Standard. European Committee for Standardization (CEN), Brussels (2002).
11. FHWA-SA-96-069R: Manual for design and construction monitoring of soil nail walls, Federal Highway Administration (FHWA), Washington D.C. (1998).
12. FHWA0-IF-03-017: Geotechnical engineering circular no. 7 soil nail walls, Federal Highway Administration (FHWA), Washington D.C. (2003).
13. FHWA-NHI-14-007: Geotechnical engineering circular No. 7: Soil nail wall reference manual, Federal Highway Administration (FHWA), Washington D.C. (2015).
14. Geoguide 7: Guide to soil nail design and construction, Civil Engineering and Development Department, The Government of the Hong Kong Special Administrative Region (GHKSAR), Hong Kong (2008).
15. Babu, G.L.S., Singh, V.P.: Reliability analysis of soil nail walls. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 3(1), 44-54 (2009).
16. Sheahan, T.C., Ho, C.L.: Simplified trial wedge method for soil nailed walls analysis. Journal of Geotechnical and Geo-Environmental Engineering 129(2), 117–124 (2003).
17. Babu, G.L.S., Singh, V.P.: Reliability based load and resistance factors for soil nailing. Canadian Geotechnical Journal 48(6), 915-930 (2011).